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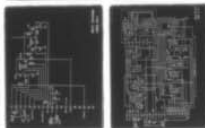
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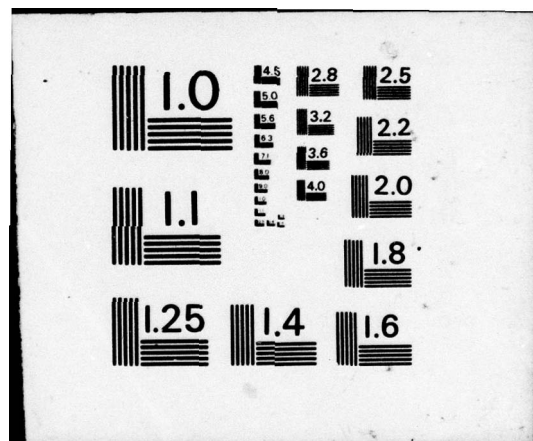
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MULTI-ELECTRODE TIME-MULTIPLEX TELEMETRY

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409 071

1 January 1977

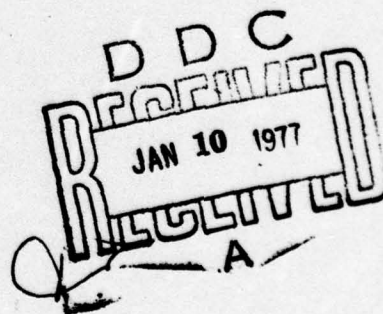
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EEG Recording	Telemetry											
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Implant Electrodes	Transcutaneous Switching											
Operational Amplifier	Waterproofing											
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Two multi-electrode time-multiplex telemetry units and their decoders are described. First, a 15-electrode totally-implanted unit that has a basic cycle rate of 400 Hz. Second, a 7-electrode partially-implanted unit that has a basic cycle rate of 4000 Hz. A remote 7-electrode stimulator-monitoring unit is briefly mentioned. ↑												

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Multi-Electrode Time-Multiplex Telemetry

This final reporting of research supported under ONR Contract #76-C-0241 is broken down into three sections: 1) a 15-electrode unit constructed for research at Rutgers Medical School; 2) ongoing research; and 3) units constructed specifically for the U.S. Navy.

1) 15-Electrode Unit Constructed for Research at Rutgers Medical School

This work is reported in the accompanying paper, "A 15-Electrode Totally Implanted Time-Multiplex Telemetry Unit", by S. Deutsch, IEEE Transactions on Communications, vol. COM-24, no. 10, October 1976.

2) Ongoing Research

We have completed the breadboard design and construction of a totally implanted remote stimulator-monitoring unit. This enables one to remotely stimulate one or any combination of seven electrodes. At the same time, the seven electrodes are continuously monitored. This will enable the experimenter to study simultaneous evoked potentials in seven selected areas of the monkey's brain. Evoked potentials may be a more effective way of assessing brain damage than the study of normally occurring EEG's.

3) Units Constructed Specifically for the U.S. Navy

During the year beginning with October 1, 1975, the Bio-engineering Section of CMDNJ-Rutgers Medical school designed and constructed a series of 6 biotelemetry units for monkeys for Dr. Marc Weiss and his colleagues at Michoud Station in New Orleans. The design and construction philosophy are similar

to that reported in the 15-electrode paper. . Therefore, only a brief discussion of the U.S. Navy units and decoder is given here.

Only 7 active electrodes are used. The units were designed to be partially implanted, with an external 3 volt battery. To make it possible to record from single neural units, relatively high switching frequencies are used. The basic cycle rate is 4000 Hz, and the channel rate is 32,000 Hz. The channel 8 input consists of a 2000 Hz 5 mV peak-to peak reference signal, and a 16,000 Hz sync signal is added to all channels. The unit is 1.4 X 2.5 X 4.2 cm in size, weighs 20 grams, and draws 10 mA. Low-frequency cutoff is at 0.2 Hz. The output is FM with a peak deviation of 75 KHz of a 30 MHz carrier at 5 mV peak channel input. The circuit is depicted on the "Navy Transmitter" sheet.

In the 15-electrode unit, the channels are first sampled at a 6400 Hz rate and then amplified in a single wideband operational amplifier. For the U.S. Navy unit, because of the much higher sampling rate, a single amplifier would have insufficient bandwidth. Therefore, each channel signal first goes to a unity-gain operational amplifier (for high input impedance) and it is then amplified in a second operational amplifier that has a nominal voltage gain of 300. Finally, the channels are sampled at a 32,000 Hz rate and fed, without further amplification, to the base of the FM oscillator.

Since each channel uses two operational amplifiers, a total of 14 is needed. This is supplied via four National Semiconductor LM 124 F flat-packs. Each of these contains four operational amplifiers, as indicated in the "Navy Transmitter" schematic.

The external battery supplies +3 V. Internally, the RF output is half-wave rectified to supply - 3 V. This arrangement is more convenient than an external center-tapped 6 V battery.

The decoder circuit is shown on the "Navy Decoder" sheet. The circuit is somewhat simpler than that of the 15-electrode decoder because the U.S. Navy unit only has 7 electrodes. Two additional drawings, "Navy Decoder Card No. 1" and "Navy Decoder Card No. 2", give the details for the two plug-in cards.

Instructions for setting the decoder knobs are given on the "Instructions for Rutgers Medical School Decoder" sheet.

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A 15-Electrode Totally Implanted Time-Multiplex Telemetry Unit

SID DEUTSCH, FELLOW, IEEE

Abstract—A 15-electrode totally implanted time-multiplex telemetry unit is described that is powered by two mercury cells in series. Transcutaneous radio frequency (RF) turn-on and magnetic turn-off are used to conserve battery power. The basic cycle rate is 400 Hz, channel rate 6400 Hz. The channel 16 input consists of a 200-Hz 5 mV peak-to-peak (p-p) reference signal, and a 3200-Hz sync signal is added to all channels. The unit is $1.5 \times 2.5 \times 8$ cm in size, weighs 41 g, and draws 3.5 mA. Low-frequency cutoff is at 0.2 Hz. The output is FM with a peak deviation of 75 kHz of a 20 MHz carrier at 5 mV peak channel input. The equivalent noise input is $2.8 \mu\text{V}$ root mean square (rms). The decoder automatically locks on the reference signal square wave with the aid of an exclusive-OR gate.

INTRODUCTION

WE now have amplifiers and CMOS digital integrated circuits that can operate on as little as 5 V. This makes it possible to design a low-noise 15-electrode totally implanted time-multiplex [1]–[6] telemetry unit that is powered by two mercury cells in series (2.7 V). Radio frequency (RF) rectification is used to generate 5 V. A design is described that features transcutaneous RF turn-on and magnetic turn-off in order to conserve battery power [7]. The signal-to-noise ratio of the system is high because amplification yields a relatively high degree of frequency modulation (FM) of the RF carrier. A 400-Hz basic cycle rate is used to get an electroencephalogram (EEG) or electrocardiogram (EKG) idealized response extending to 200 Hz. The channel 16 input, used for initial synchronization, consists of a 200-Hz 5-mV peak-to-peak (p-p) reference signal. In addition, a 3200-Hz square-wave synchronizing signal is added to all channels.

The research goal is to obtain an integrated picture of electroencephalographic activity, either in widely separated regions (especially those involving bilateral symmetry) or in a local region, such as the visual or auditory cortex, of socially interacting epileptic monkeys [8]. The advantage of a totally implanted unit, of course, is that the animal can be completely ambulatory, with only a small protuberance to reveal the presence of the transmitter [9].

Including batteries that can operate 100 hours before

replacement, the unit is $1.5 \times 2.5 \times 8$ cm in size and weighs 41 g. Although it was designed for subcutaneous implantation in monkeys, it can of course be used for EEG and/or EKG monitoring of any animal that can carry 41 g.

The implant unit is designed to handle the signals picked up by relatively gross extracellular electrodes that are embedded in brain or heart tissue, up to 2 mV peak [10], [11]. This is larger, by an order of magnitude, than the signals picked up by relatively remote surface electrodes.

Ideally, the physiological signal bandwidth should extend to dc. Experience shows, however, that each input may contain a relatively large spurious dc component due to 1) "battery" action if the electrodes and common ground strip are made of dissimilar materials, and due to differences in surface layer even if they are made of the same material; and 2) a few millivolts due to integrated circuit rectification of the relatively strong RF field that surrounds the FM transmitter coil. Physically small $1\text{-}\mu\text{F}$ capacitors are therefore used in series with each channel input to block dc components. With an effective input resistance per channel of $1.6 \text{ M}\Omega$, the nominal low-frequency cutoff is 0.1 Hz.

FM is used in order to get a receiver output that is independent of RF signal strength [12]. Since it is convenient to use commercial equipment, the unit described below is adjusted to have a peak deviation of 75 kHz of a 20-MHz carrier at 5-mV peak channel input. A frequency converter is used to beat down to the commercial IF of 10.7 MHz.

BLOCK DIAGRAM OF IMPLANT UNIT

A block diagram of the implant unit is depicted in Fig. 1. Standard readily available integrated circuit (IC) flat-packs are employed for maximum flexibility. There is a total of 5 flat-packs. Although some reduction in volume could be achieved via a special-purpose single flat-pack, an irreducible minimum volume is dedicated to the batteries, terminal board, input blocking capacitors, and RF transmitter coil. The epoxy layer should be at least 2 mm thick.

One-half of a CD4001AK acts as a 6400-Hz astable multivibrator clock (C). The waveforms are shown in (1) through (7) of Fig. 2. A CD4024AK binary counter supplies C/2, C/4, ..., C/32 square waves. (The counter actually has 7 stages, but the C/64 and C/128 outputs are not used.) The C/2, C/4, and C/8 signals [waveforms (3), (4), and (5)] cause two CD4051AK flat-packs to sequentially close input electronic switches. The C/16 signal [waveform (6)] turns on the first CD4051AK unit, which covers the reference channel plus channels 1 through 7, and C/16 inverted turns on the second unit, channels 8 through 15.

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The author is with the Bioengineering Section, Surgery Department, CMDNJ–Rutgers Medical School, and Electrical Engineering Department, Rutgers University, Piscataway, NJ 08854.

To turn the unit off, an external magnet is held near the implant unit. It causes a magnetic reed switch to close, thereby short-circuiting the oscillator bias supply. This turns the transistor base "off" without wasting battery power. The magnetic reed switch is 0.1 in in diameter by 0.3 in long, and is positioned towards the top of the unit.

There is a battery drain of about 3.5 mA, which gives a life of some 100 hours with RM-630 mercury cells which are 5/8 in in diameter by 1/4 in thick. With an average battery shelf life of 2 years, there is no compelling reason to use the unit as soon as it is implanted, in contrast with devices that cannot be turned on and off. When the cells are used up, a hacksaw is employed to sever them from the remainder of the unit. New cells are attached, positioned in the mold, and covered with paraffin and epoxy. The new and old epoxies adhere satisfactorily.

The transistor type has been omitted from the schematic because there are many physically-small silicon n-p-n (or p-n-p) types that can be used for the oscillator. We pretest the transistor in a 100-MHz Colpitts oscillator circuit.

The actual frequency used for the RF carrier is a compromise based on the following four considerations [7].

- 1) The advantage of operating at a relatively low frequency, for an implanted device, is that tissue losses are reduced, so that the oscillator Q can be correspondingly higher. One can show that the Q , based on eddy current losses, is inversely proportional to frequency.

- 2) Another advantage of low frequencies is that depth of penetration increases, so that one can work with larger animals. For a central-body implant, the animal's diameter can be as much as 22.5 cm (9 in) at 100 MHz, and 50 cm (20 in) at 20 MHz.

- 3) An argument for operating at higher frequencies is that the antennas become more effective.

- 4) There is an important advantage of operating at 100 MHz in that one can use standard low-cost FM receiving equipment.

Our experience is that the improved reliability and stability of an implanted oscillator at 20 MHz as compared to 100 MHz is the most important consideration. We use a standard FM receiver in conjunction with a converter. The converter contains a 30.7 MHz tunable local oscillator which provides a 10.7 MHz IF output. The latter is fed to the IF input of the FM receiver.

As shown in Fig. 3, the amplifier output feeds through a 100-k Ω resistor to the oscillator transistor base, and 3200-Hz channel sync is added via a 390-k Ω resistor. Here they vary the base current, which in turn varies the base-charging capacitance, thus yielding FM. The resistance values are nominal; we actually use values that correspond to a peak deviation of 75 kHz with 5 mV peak channel input.

The physical layout of the implant unit is outlined in Fig. 4 and a photograph is shown in Fig. 5. The unit is curved to better conform to the curvature of the animal's body. "Cordwood" construction is used in which the electronic components are held between two parallel strips of standard circuit board that have holes spaced 0.05 in apart. The assembly is first embedded in paraffin for waterproofing and then in

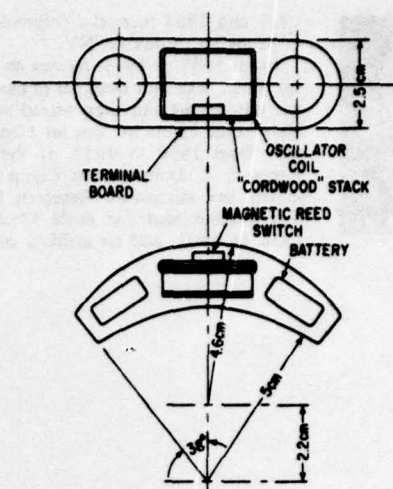


Fig. 4. Physical layout of implant unit.

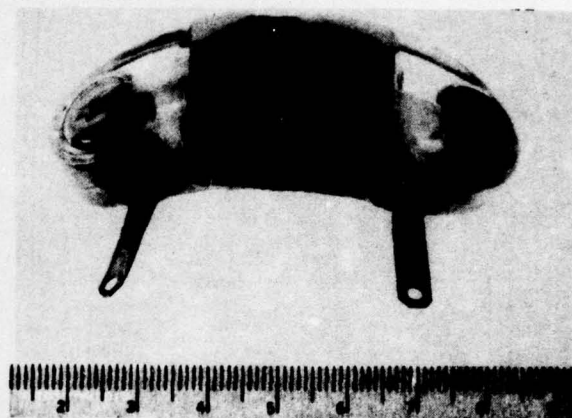


Fig. 5. Photograph of implant unit. Units shown on ruler are centimeters.

epoxy. These are subjected to a partial vacuum to remove gases and moisture. The technique follows the methods that are employed in the heart pacemaker industry.

BLOCK DIAGRAM OF THE DECODER

The multiplex signal out of the FM receiver must, of course, be decoded into 15 channel outputs. This is more difficult than in a conventional time-multiplex communication system because, as the animal moves around the cage, some combinations of location and head orientation are such that the received RF signal becomes practically zero, so that synchronization is lost.

The block diagram, waveforms, and circuit diagrams are shown in Figs. 6, 2, and 7, respectively.

The philosophy used here is to electronically switch from a "search" mode when the multiplex signal is absent or first appears, to a "synchronized" mode when the multiplex signal is "captured." A phase-locked loop (PLL) is employed for synchronization.



1947 and 1955 from the Polytechnic Institute of Brooklyn, Brooklyn, NY.

From 1935 to 1944, he was an Electric Motor Technician and Designer of electro-mechanical equipment and then served with the U.S. Navy until 1946. He was an Electronics Engineer from 1950 to 1954, at the Polytechnic Research & Development Company, and then joined the Microwave Research Institute. He was a consultant for Budd Electronics from 1958 to 1961, and an affiliate of the Rocke-

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Dr. Deutsch is the author of *Theory and Design of Television Receivers and Models of the Nervous System*. He is a Fellow of the Society for Information Display.

The multiplex input is first amplified, and inverted if necessary (because the phase supplied by the FM receiver is, in general, unknown), so that the 3200 Hz component has an amplitude of 2 V p-p. It then feeds two sample-and-hold CD4051 commutators that perform an operation which is inverse to that of the implant unit. Sampling pulses (14) turn the CD4051's on during the central 78 μ s of each channel. They are derived from waveforms (8) and (2) via the logic operation $D = AC + A'C'$. The sampling pulses are combined with waveform (6) so that CD4051 #1 is turned on in accordance with logic operation $E = B + D$ [waveform (15)]. Unit CD4051 #2 is turned on in accordance with $F = B' + D$ [waveform (16)]. Each sampled level is held constant by means of 0.1- μ F capacitors until the next sampling period, 2500 μ s later.

If the multiplex input has been "captured" by the PLL, the reference-channel output of the sample-and-hold circuit is a 200-Hz square wave, waveform (17). This is compared with the 200-Hz output of counter #1, waveform (7), in a CD4030 exclusive-OR gate. The output of the gate is low-pass filtered. Except for narrow 39- μ s periods, as shown in waveform (18), the exclusive-OR gate output is positive, so the average dc value supplied by the low-pass filter is +6 V. This is used to throw CD4066 electronic switches into the "synchronized" mode.

If the multiplex input has *not* been captured, the reference-channel output of the sample-and-hold circuit consists of more or less randomly fluctuating rectangular waves, which in turn leads to a similar noise-like output from the exclusive-OR gate. In this event the average dc value supplied by the low-pass filter is near zero, so that the electronic switches remain in the "search" mode.

In the "synchronized" mode, the comparator input for the PLL is switched from the 200-Hz square wave (13) to the 3200 Hz square (12). Notice that (12) lags the 3200-Hz component of (1) by 90°, as it should. The 3200-Hz component of the multiplex signal then yields very stable PLL synchronization.

Two refinements are added by means of the electronic switches: In the "search" mode, a relatively large capacitor is used to filter out high-frequency components of the multiplex signal input to the PLL, relative to the 200-Hz component. This greatly improves the threshold level at which the PLL locks on reference-channel sync. In the "synchronized" mode the 3200-Hz components are restored.

In the "search" mode, the decoded outputs of channels 1 to 15 are inhibited by opening $B+$ and $B-$ supplies of emitter-follower output stages. Since the EEG output can look very much like a random-noise signal, it is important to inhibit the output unless bona-fide synchronization exists.

CIRCUIT DIAGRAM OF THE DECODER

Most of the details of the decoder circuit, Fig. 7, have already been covered in discussing the block diagram.

The multiplex input is amplified in a single stage. The signal then goes to a phase inverter. After the proper phase is selected by the polarity switch, it feeds to isolating emitter

followers. One branch goes to a low-pass filter with a time constant of 110 μ s in the "search" mode and 10 μ s in the "synchronized" mode. The filter output becomes the PLL data input.

The other multiplex signal branch feeds the sample-and-hold CD4051 units. The "hold" components are 0.1 μ F capacitors. The channel 1 to 15 outputs are disabled in the "search" mode. The reference-channel output is amplified to bring it up to 12 V p-p for exclusive-OR multiplication with the 200-Hz output of binary counter #1. The exclusive-OR output is low-pass filtered with a time constant of 50 ms. The "sync threshold" potentiometer is a screwdriver control that adds a dc component such that the CD4066 switch barely closes when the exclusive-OR low-pass filter output is +6 V. It is the closing of this electronic switch that places the decoder in the "synchronized" mode.

The logic circuits employ two CD4001 NOR gate IC's and a single ex-OR gate IC. Each of these IC's has four sections.

ACKNOWLEDGMENT

Construction and testing of the implant and decoder units are credited to the expertise of J. Morgan.

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★

Sid Deutsch (A'44-M'55-SM'69-F'75) was born in New York, NY on September 19, 1918. He received the B.E.E. degree in 1941 from Cooper Union, New York, NY, and the M.E.E. and D.E.E. degrees in

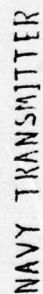


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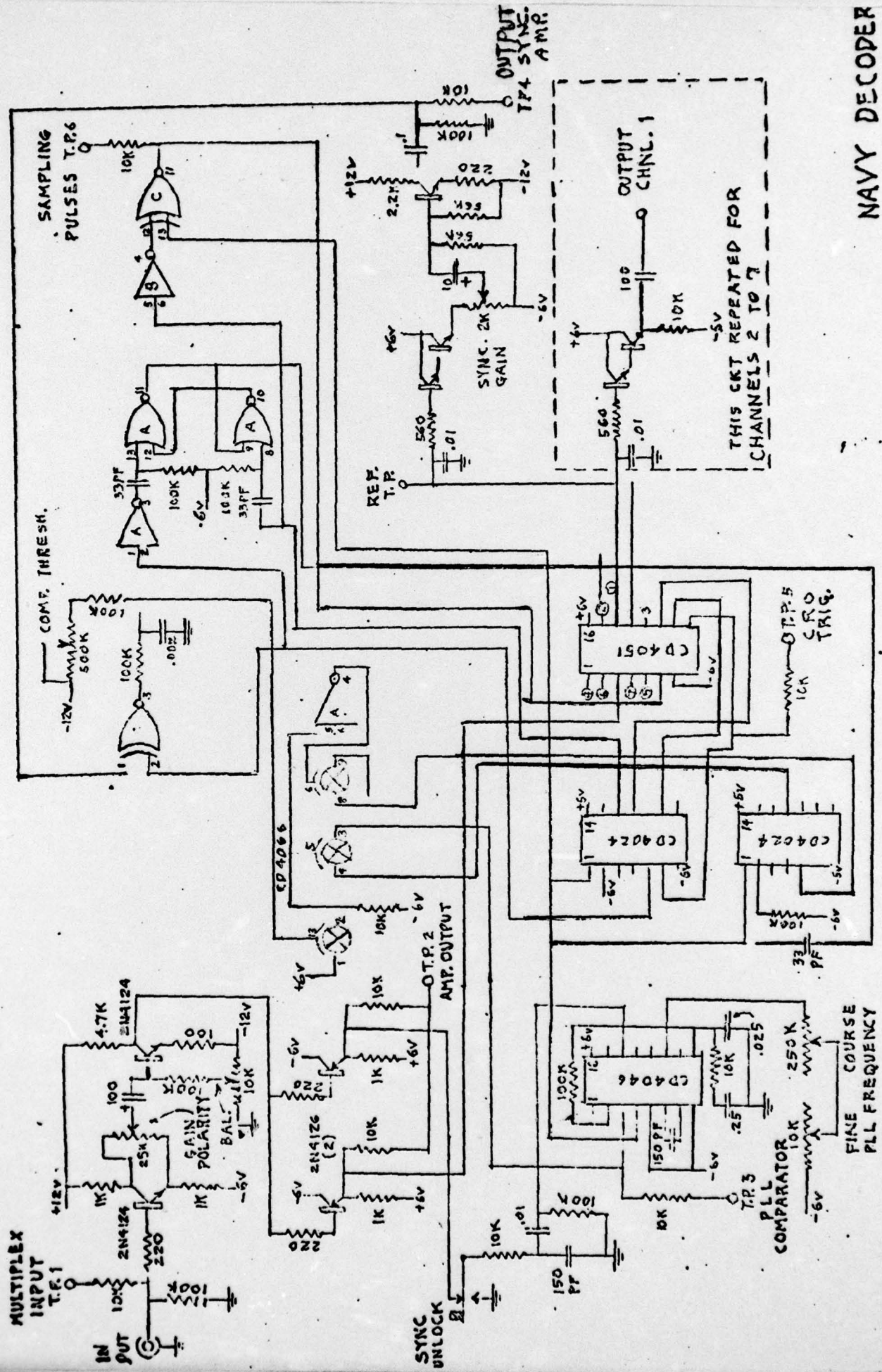
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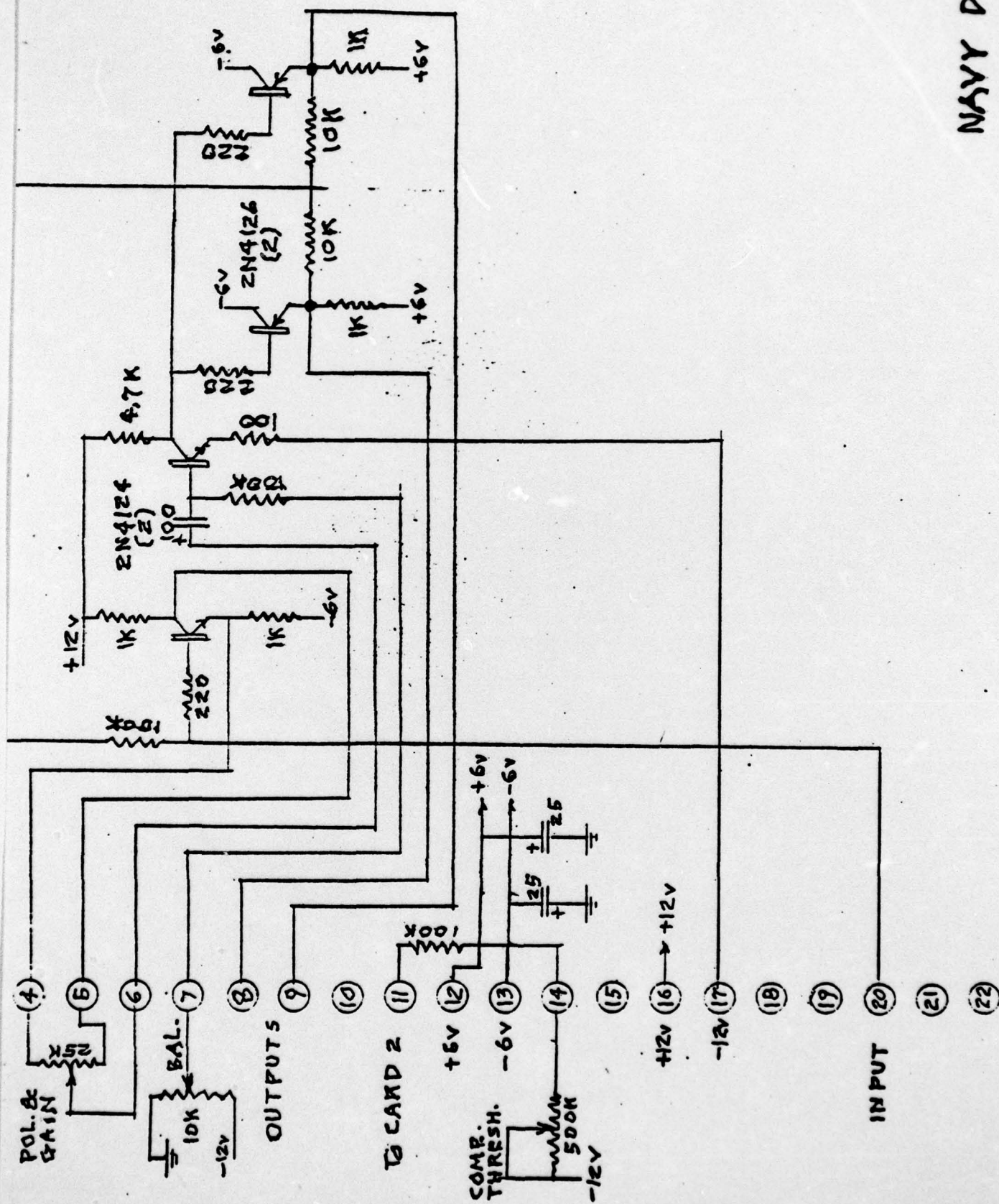


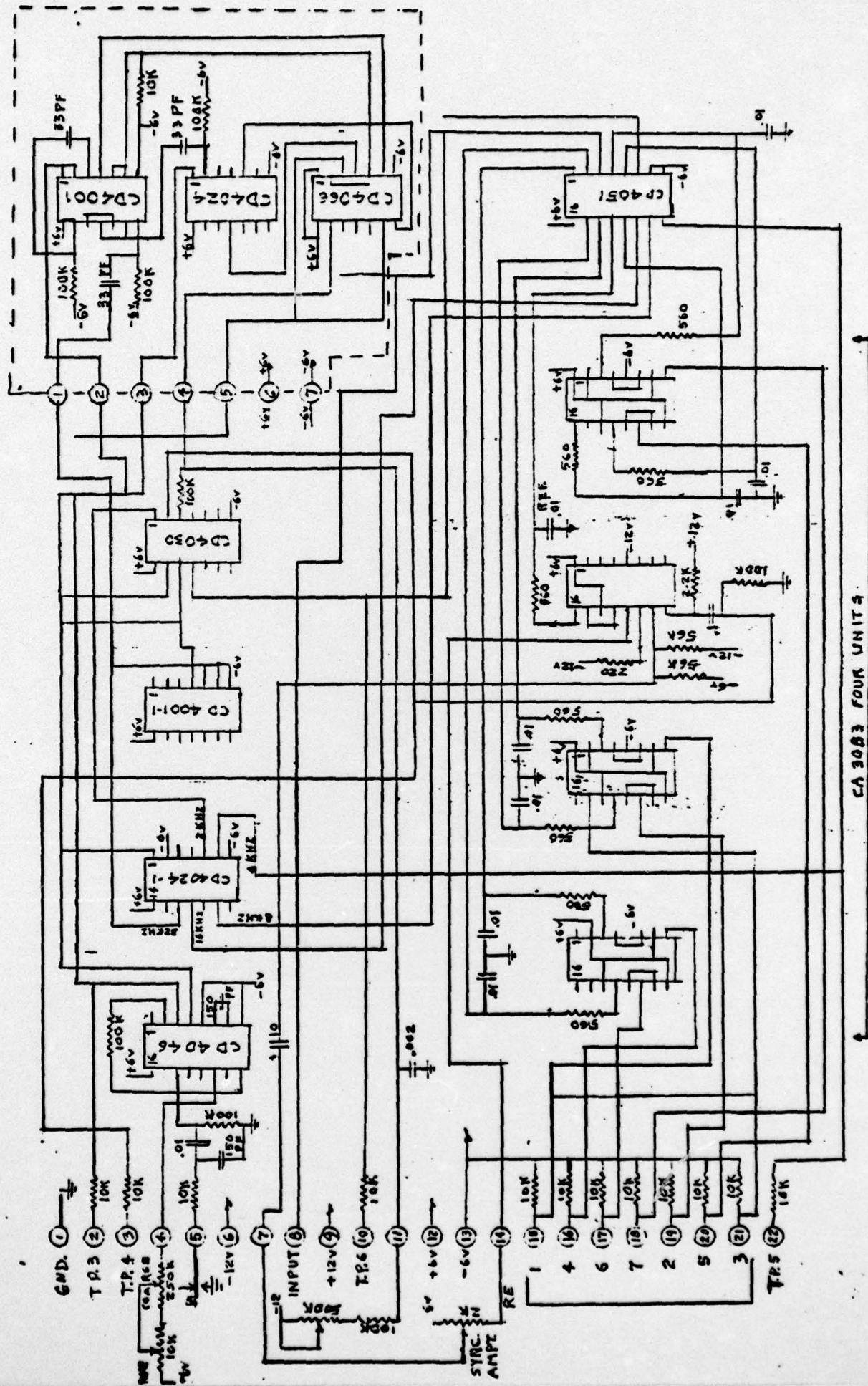
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NAVY DECODER
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NAVY DECODER
CARD No. 1

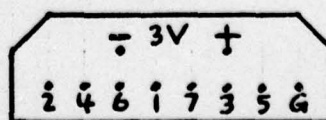
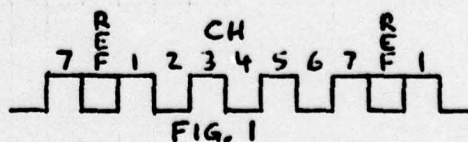
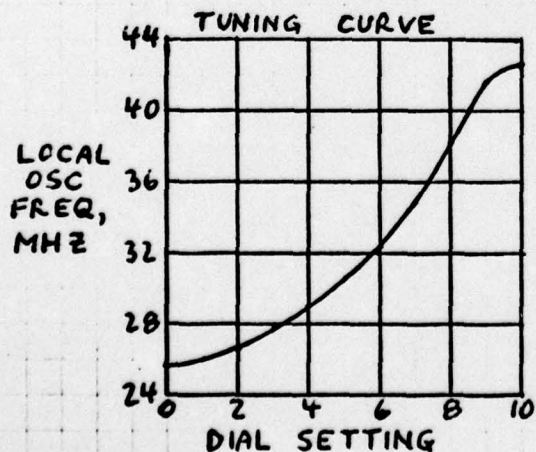




NAYY DECODER
CARD No. 2

Instructions for Rutgers Medical School Decoder

1. Turn "Comparator Threshold" and "Sync Amp Gain" fully clockwise. Monitor "Amplifier Output" TP. Set "Balance" for zero DC output with no signal input.
2. Connect 30 MHz from transmitter to rear "RF In" of Decoder. Connect rear "IF Out" of Decoder to FM receiver "IF In". Connect Discrim. output of FM receiver to rear "Multiplex In" of Decoder.
3. Monitor "Multiplex Input" TP. Set "Convert Frequency" fine tuning to center (dot on top). Set coarse tuning to 10.7 MHz above carrier per tuning curve below. Tune for clean, noise-free multiplex signal. Check for zero DC offset.
4. Monitor "Amplifier Output" TP. Adjust "Amplifier Gain, Polarity" for 6V p-p Multiplex signal (16 kHz square wave). Set CRO controls for Reference Signal overlap (+ and - Reference Signals in same time slot as shown in Fig. 1). Polarity should be such that channels on each side of Reference Signal are positive-going. Set CRO controls so that 8 Divisions = 8 channels of multiplex signal.
5. Monitor "CRO Trigger" TP. Depress "Sync Unlock" button. Set "PLL Frequency" fine control to center (dot on top). Set coarse control so that one cycle of square wave = 8 divisions on CRO.
6. Use "CRO Trigger" TP to externally trigger CRO. Monitor "Amplifier Output" TP and "CRO Trigger." Reference signal should start at negative-going edge of 4 kHz square wave. Verify 8 channels = 1 cycle of square wave.
7. Monitor "Sync Amp Out" TP. Adjust "Sync Amp Gain" for 12V p-p.
8. Monitor "PLL Comparator" TP. The signal should be a 2 kHz square wave. Adjust "Comparator Threshold" so that 2 kHz square wave barely switches over to a clean 16 kHz square wave.
9. Monitor "Reference" Channel Out. The signal should be a 2 kHz square wave.
10. Monitor "Multiplex Input" and "Sampling Pulses". The negative-going sampling pulses should occur within each channel pulse.



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